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Aluminum Formability Extension through Superior Blank Processing

X SUN (PI)
PACIFIC NORTHWEST NATIONAL LABORATORY
RICHLAND, WA, USA

2015 DOE VEHICLE TECHNOLOGY PROGRAM REVIEW
JUNE 8-12, 2015

Project ID#: LM078

Overview

Timeline

- Start: Oct. 2011
- End: Sep. 2015
- 95% Complete

Budget

- DOE - $1,200K
  - FY12 - $400k
  - FY13 - $300k
  - FY14 - $500k
  - FY15 - With carryover funds
- Industries (in-kind) - $675K
  - Industry - $225k/YR FY12 – FY14

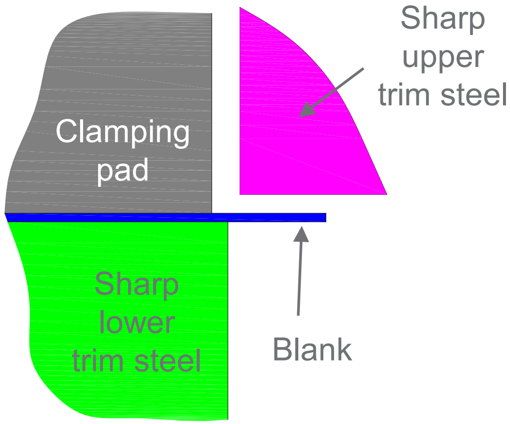
Barriers

- Manufacturability:
  - Difficult to manufacturing with current infrastructure
- Performance:
  - Room temperature formability of the aluminum sheet can be reduced by as much as 50% as a result of inadequate blanking, piercing, and trimming operations
- Predictive modeling tools:
  - Lack of adequate predictive modeling tools

Partners

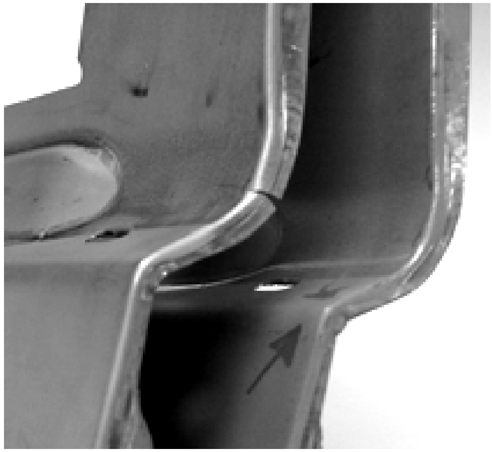
- Ford Motor Company
- Oakland University

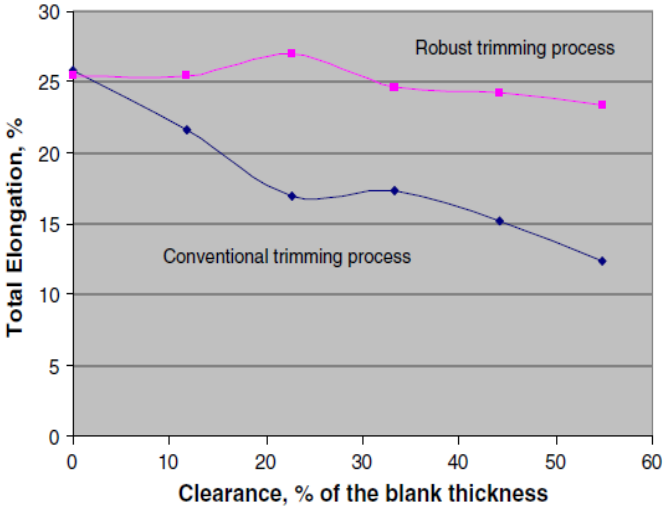
Motivation: Conventional Trimming Process



- Trimmed surface quality is very sensitive to the alignment accuracy of the upper and lower dies.
- Burrs, slivers and splits are typical defects encountered in conventional trimming.
- Tooling alignment is especially difficult in curved areas of the trim line.
- Insufficient die stiffness can be a problem due to the increased trimming forces necessary for AHSS steel.

Examples of splits in production parts





S.F. Golovashenko, International Journal of Mechanical Sciences 48, 2006

Project Objectives

- Objectives: To develop, prototype, and demonstrate superior methods of blanking, piercing, and trimming operations to enhance room temperature sheet aluminum formability by:
  - Building validated predictive capabilities to quantify relationships between trimming condition to trimmed edge quality and to subsequent stretchability:
    - Create computational capability and framework to integrate materials processing information into subsequent coupon- and part-level performance simulations
  - Enhancing coupon- and part-level formability by controlling key edge quality indicators:
    - Edge stretchability
    - Hole expansion

Deliverables and Milestones

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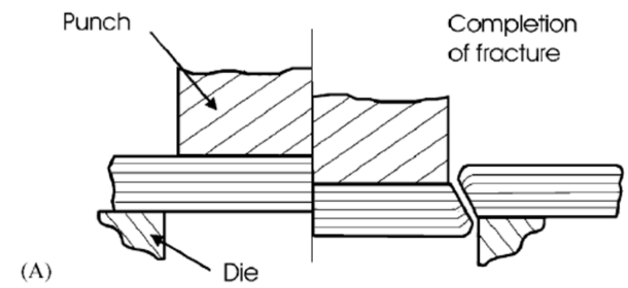
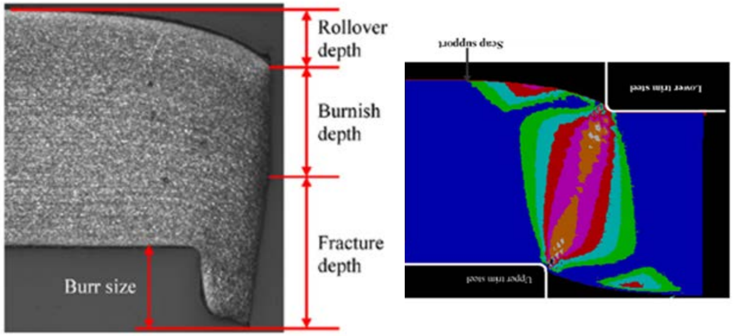
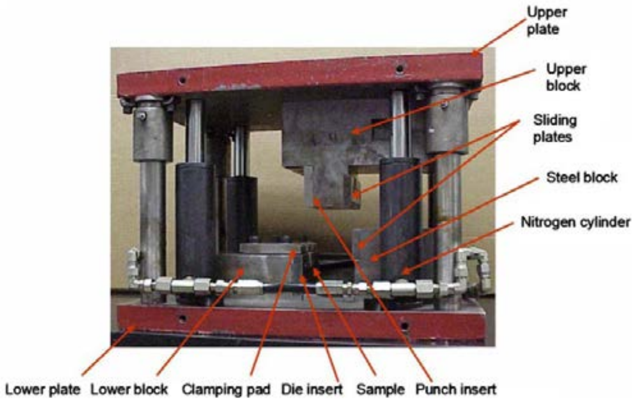
Date	Milestone or Go/No-Go Decision	Description	Status
12/31/2012	Milestone	An experimentally validated trimming process simulation model	Completed
12/31/2012	Go/No-Go Decision	The predicted burr geometry with greater than 90% accuracy compared with experimental measurements	Met
9/30/2013	Milestone	An experimentally validated stretchability simulation model incorporating trimmed edge conditions	Completed
9/30/2013	Go/No-Go Decision	Achieve on average 50% improvement for RT formability	Met
9/30/2014	Milestone	A demonstrated prototype trimming process that enhances the overall formability of aluminum sheet	Completed
3/31/2015	Milestone	Validate hole-expansion prediction capability for different aluminum alloys for failure strain to within 90% of measured values	Completed

Technical Approaches

- Task 1. Literature review and software capability analysis (PNNL and Ford)
- Task 2. Cutting process simulation and experimental validation (PNNL, OU and Ford)
  - Trimming model development
  - Trimming model validation with experiments
  - Obtain damage statistics and process parameter relationship
- Task 3. Forming process simulation and experimental validation (PNNL, OU, Ford)
  - Stretching model development with trimming history
  - Stretching model validation with experiments
  - Obtain quantitative relationship between edge stretchability and edge quality indicators
- Task 4. Develop optimized process parameters based on ability of sheared surface to stretch (PNNL, Ford)
  - Establish process parameter
  - Prototype process development on lab scale
  - Demonstrate technology on commercial relevant component scale

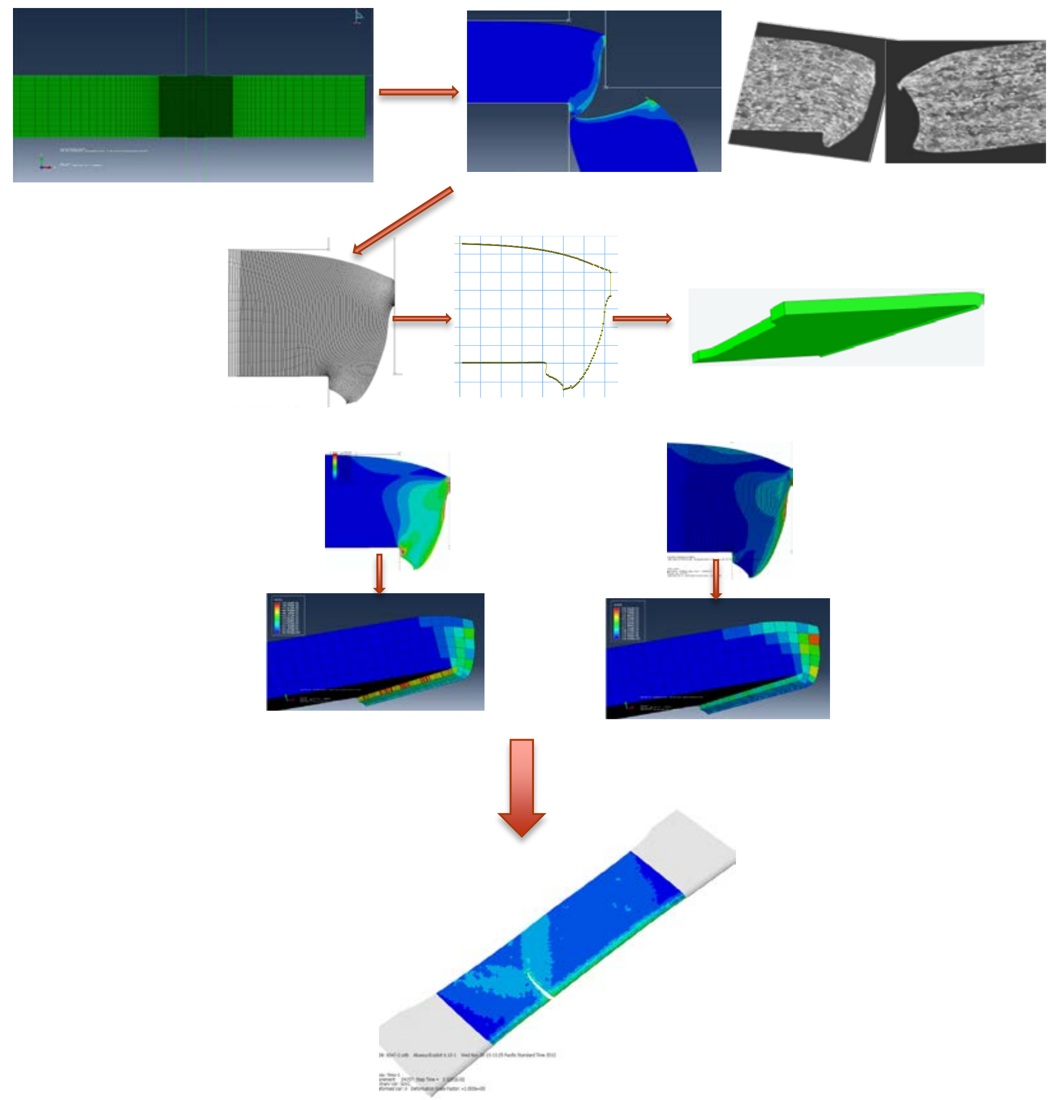






Previous Technical Accomplishments:
Integrated Framework from Trimming to Stretching

- Trimming simulation
- Burr geometry
- Initial plastic strains
- Cutting induced damage
- Cutting induced residual stresses
- Material model
  - Work hardening law
  - Damage model
  - Taylor factor used to consider grain level heterogeneity
- Failure mode
- Ductility (or stretchability)
- Cases studied:
  - Traditional Trimming/Tensile Stretching
  - Advanced Trimming/Tensile Stretching
  - Hole piercing/Expansion



X. H. Hu, X. Sun, S. F. Golovashchenko, *Computational Materials Science* 85, **2014.**
X. H. Hu, K. S. Choi, X. Sun, S. F. Golovashchenko, *Journal of Manuf Sci & Eng* 136, **2014**.

Previous Results on Stretching Simulations:
- Quantitative Model Validation

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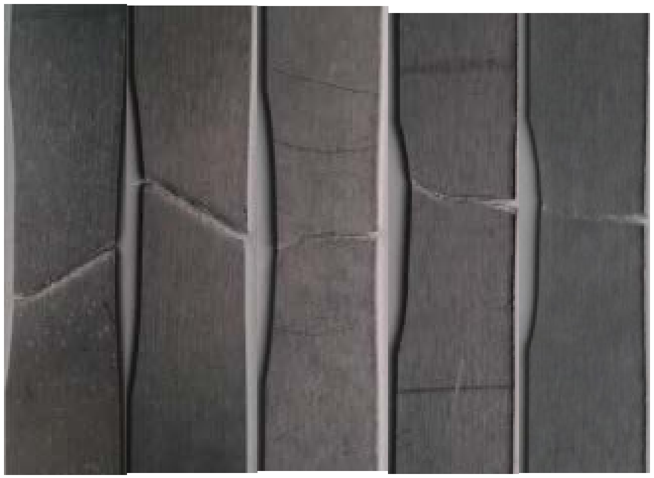
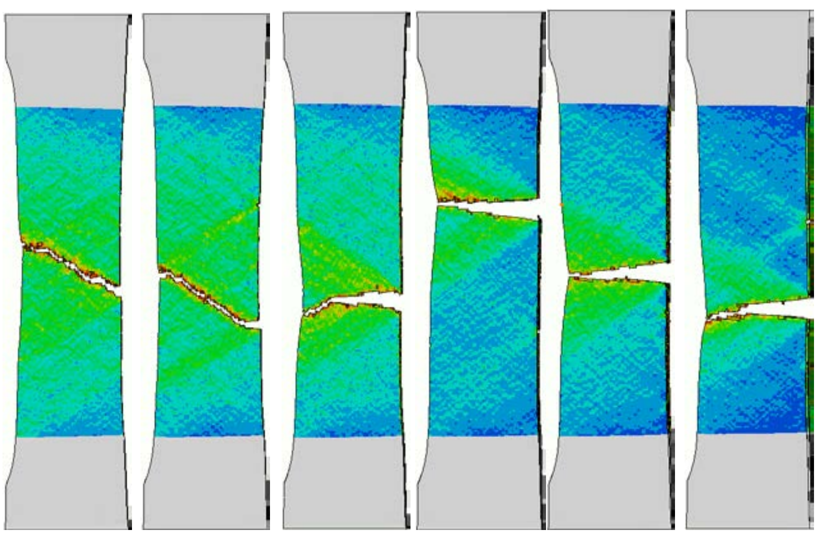
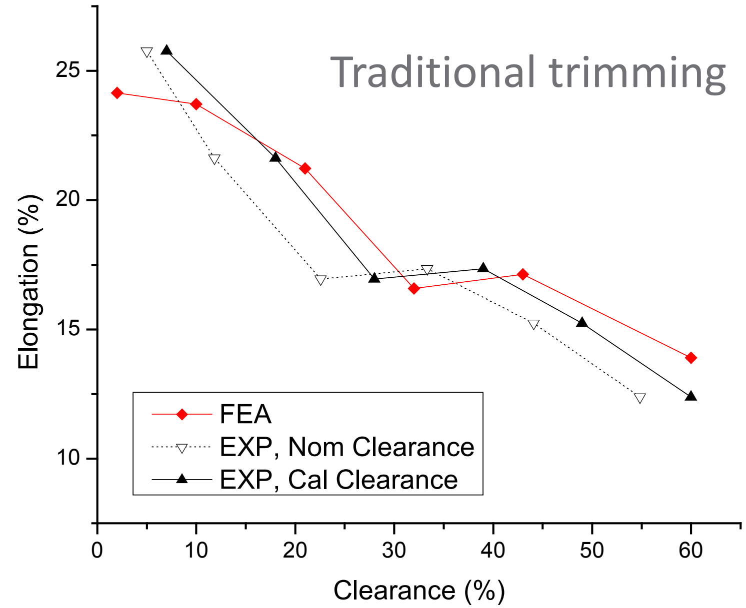


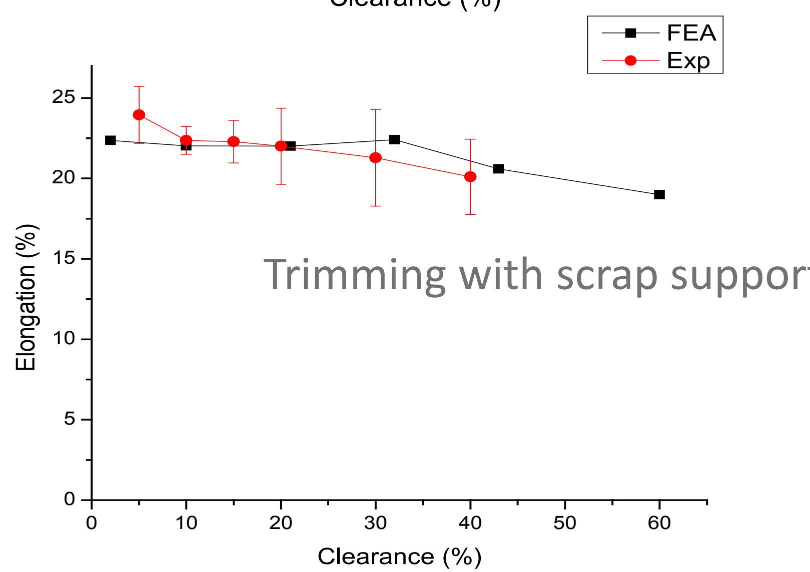
OU/Ford experiments

5% 10% 20% 30% 40%



2% 10% 21% 32% 43% 60%

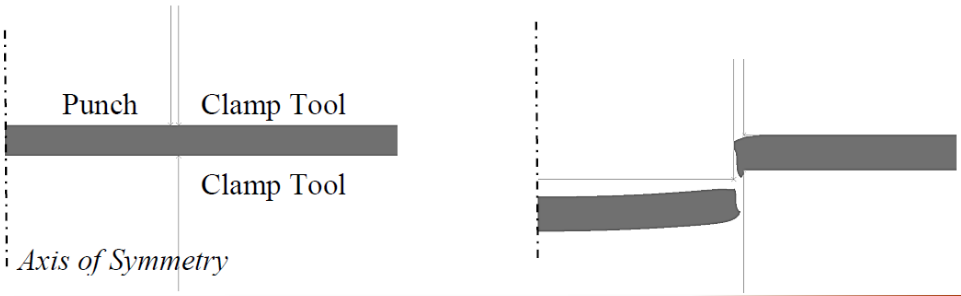




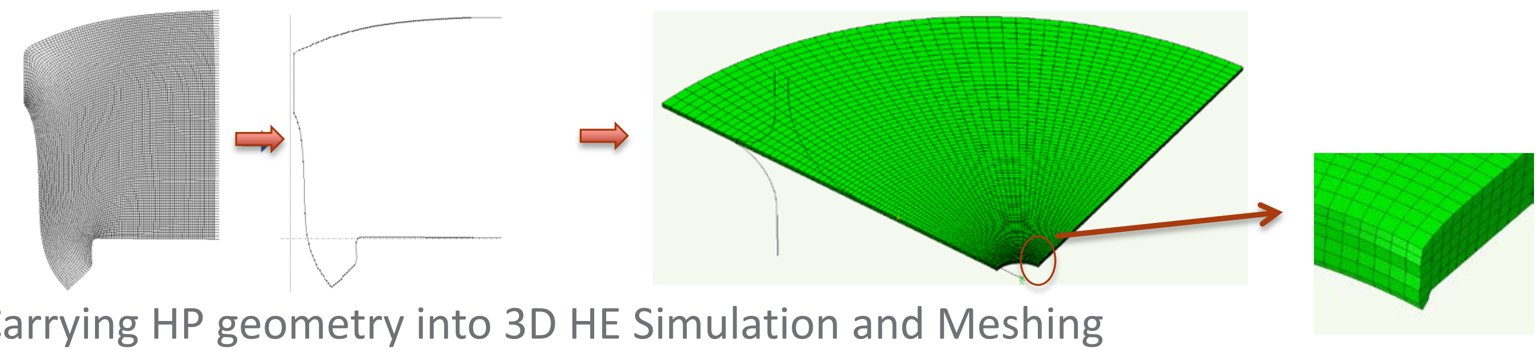
X. H. Hu, X. Sun, S. F. Golovashchenko, *Computational Materials Science* 85, **2014.**

Integrated Computational Framework

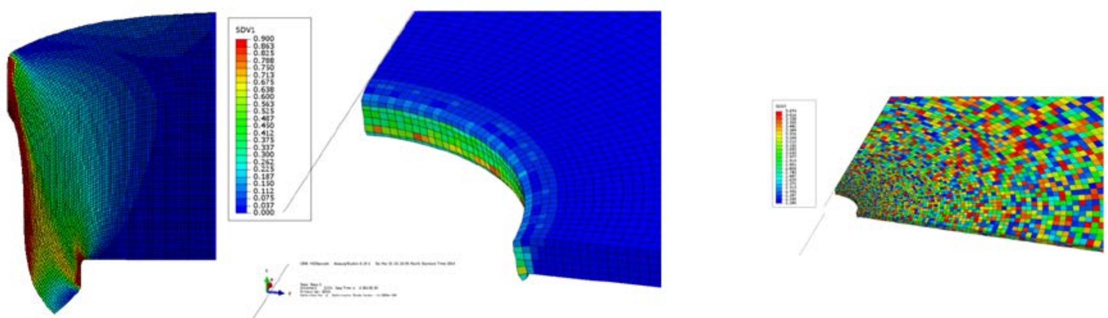
Hole Piercing (HP) to Hole Expansion (HE) Simulations



2D HP Simulation



Carrying HP geometry into 3D HE Simulation and Meshing

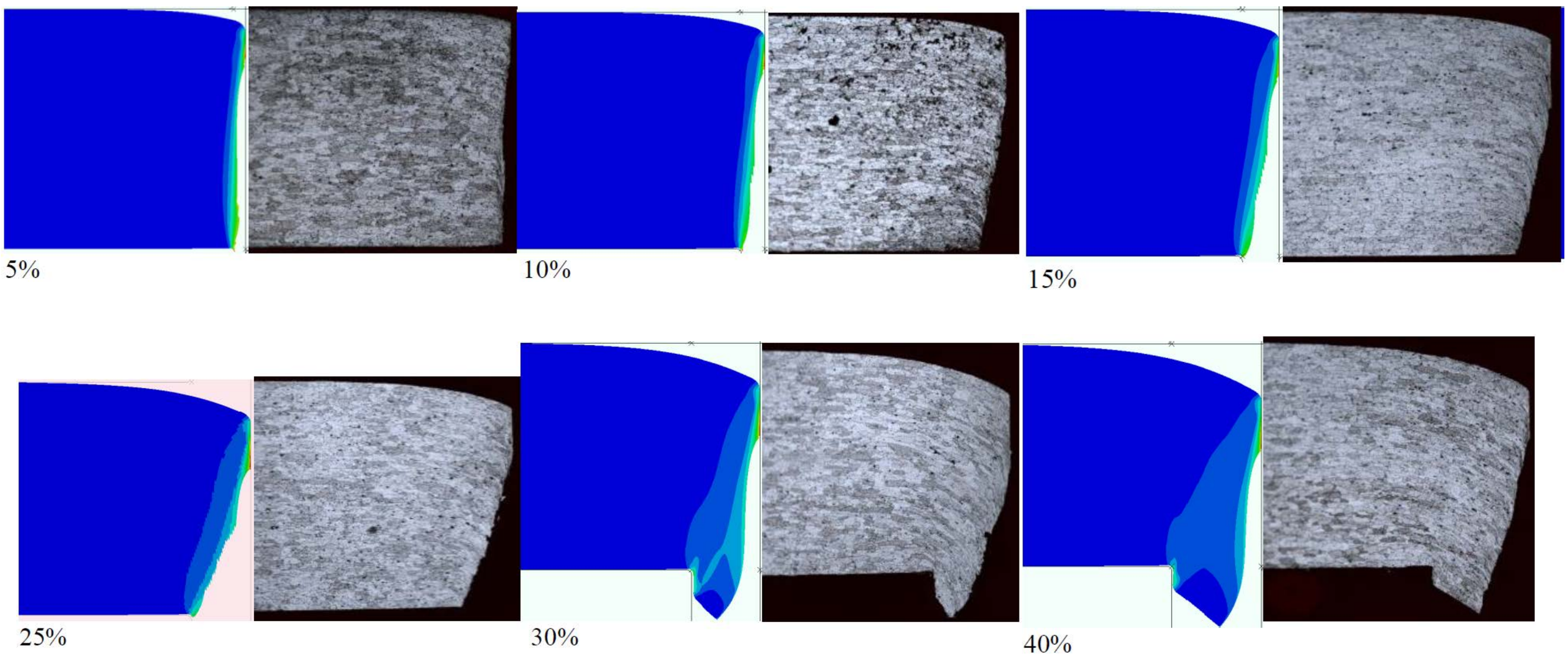


Mapping Field Variables and Considering Heterogeneity and axis-symmetry

X. H. Hu, X. Sun, S. F. Golovashchenko, *Computational Materials Science, submitted*

Prediction and Experiments on Burr Geometry

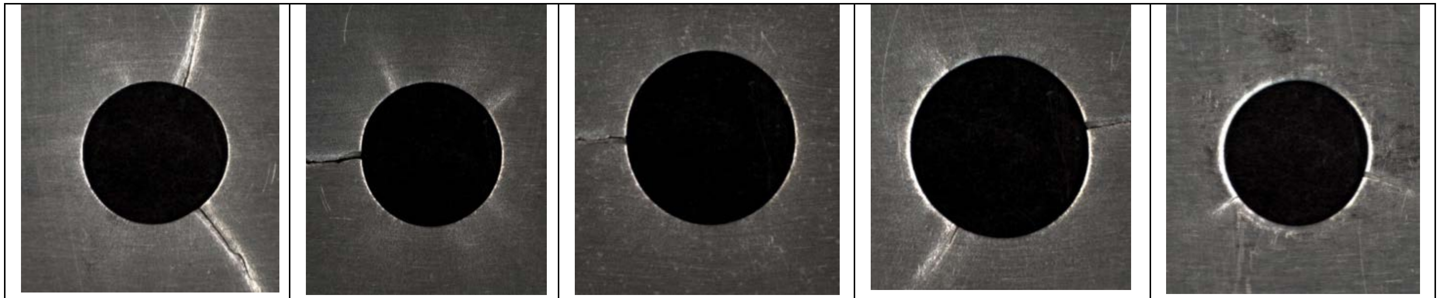
Hole Piercing (AA6111)



Ford/OU Experiments and PNNL Predictions both show that no burr formation before clearance of 25% and vice versa.

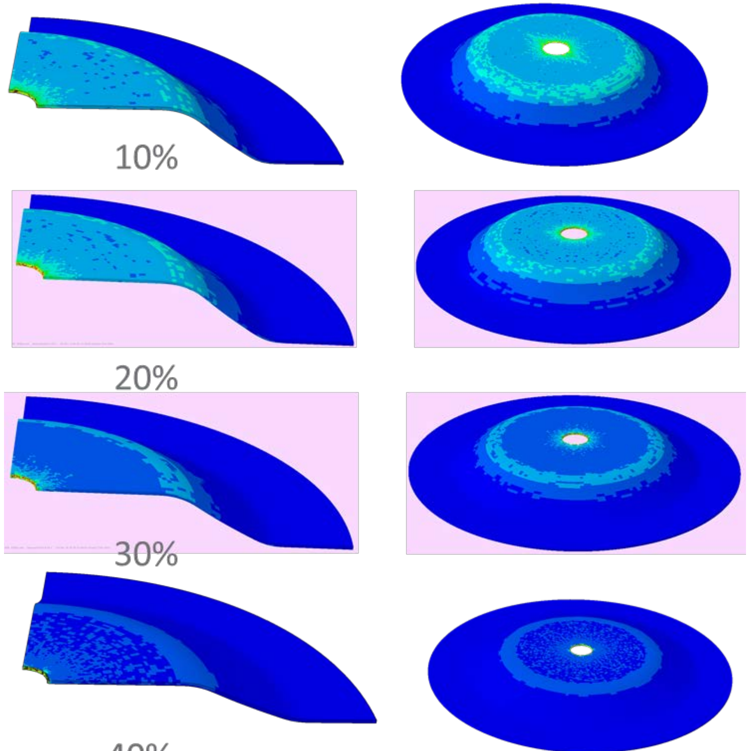
Prediction and Experiments on HER

Validation of Hole Expansion Predictions (AA6111)

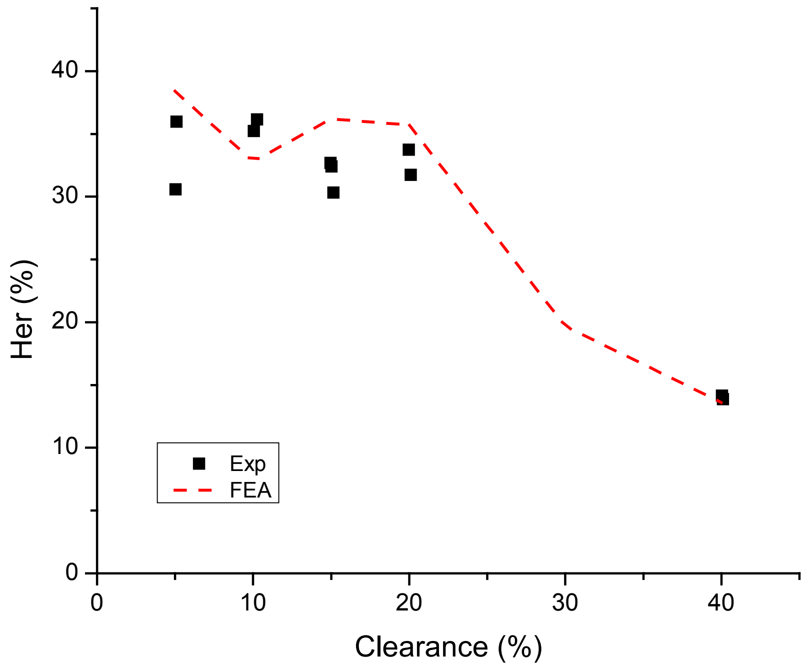


5% clearance	10% clearance	15% clearance	20% clearance	40% clearance

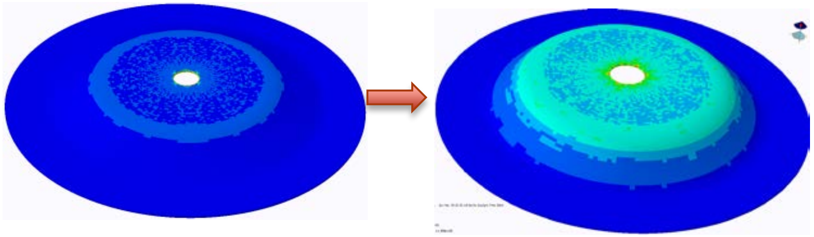
OU/Ford experiments



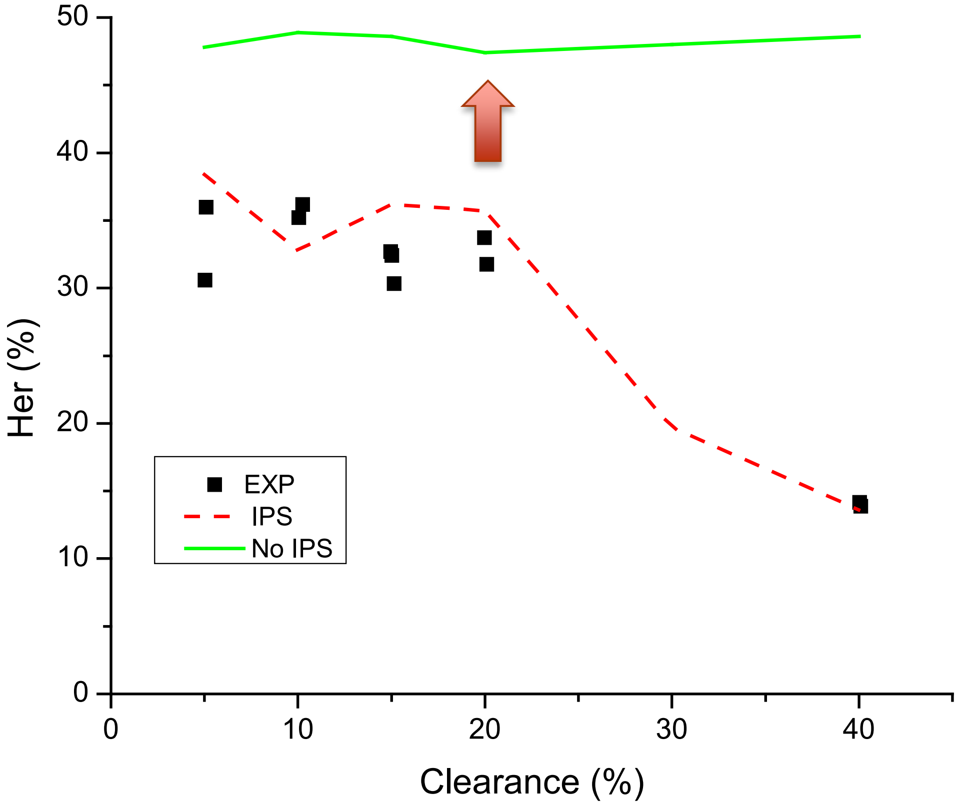
Predicted and measured HER



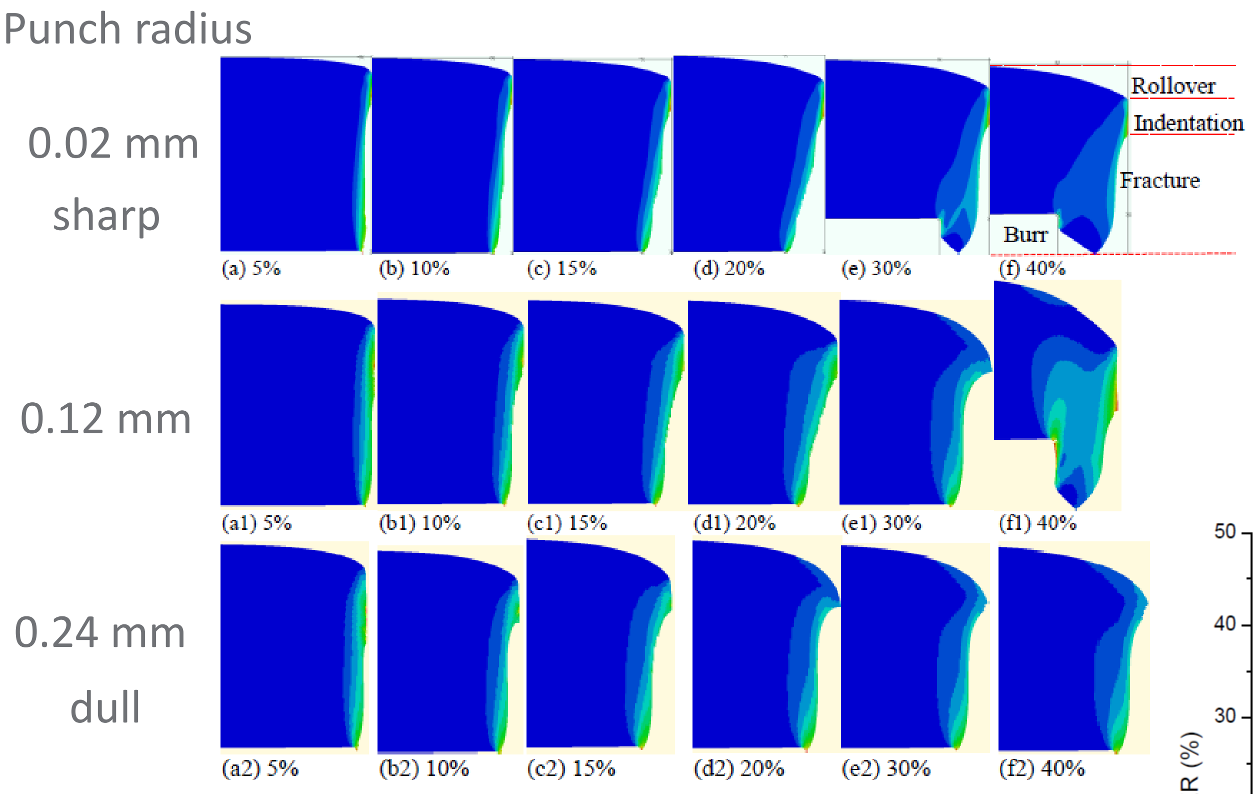
Hole Piercing to Hole Expansion:
Effects of removing plastic strain after hole piercing

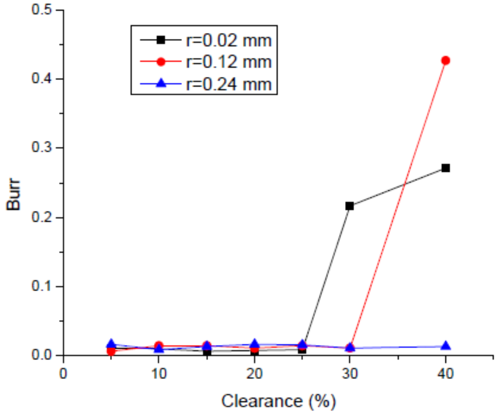


40% Clearance

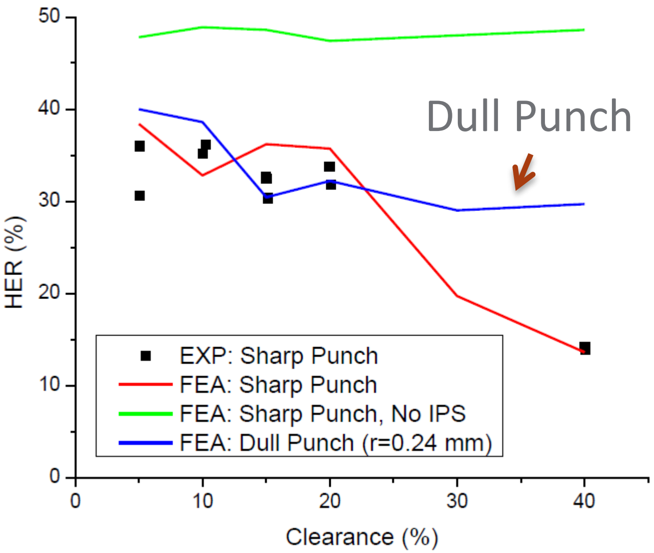


Hole Piercing to Hole Expansion:
Effects of dull punches during hole piercing





No burr for all clearances with dull punch



Hole Piercing to Hole Expansion:
Effects of alloys: AA6111-T4 vs AA6022

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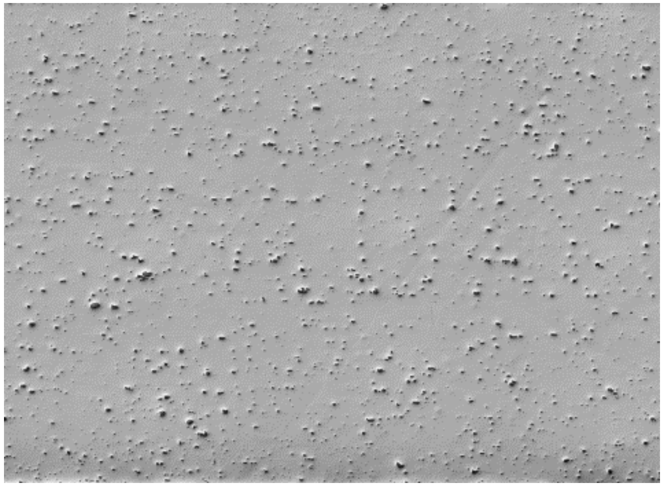
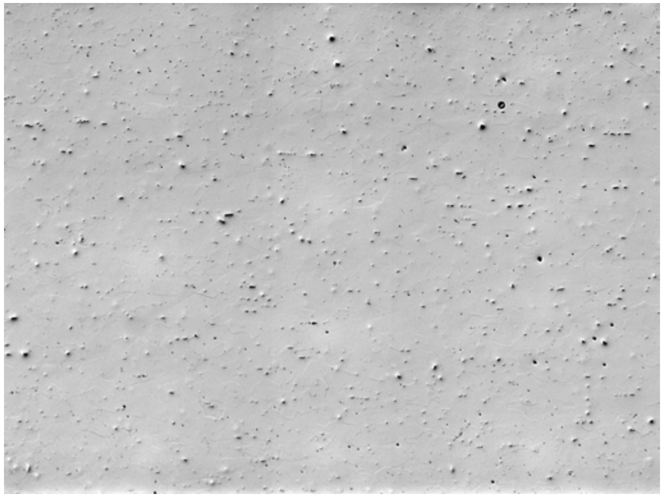
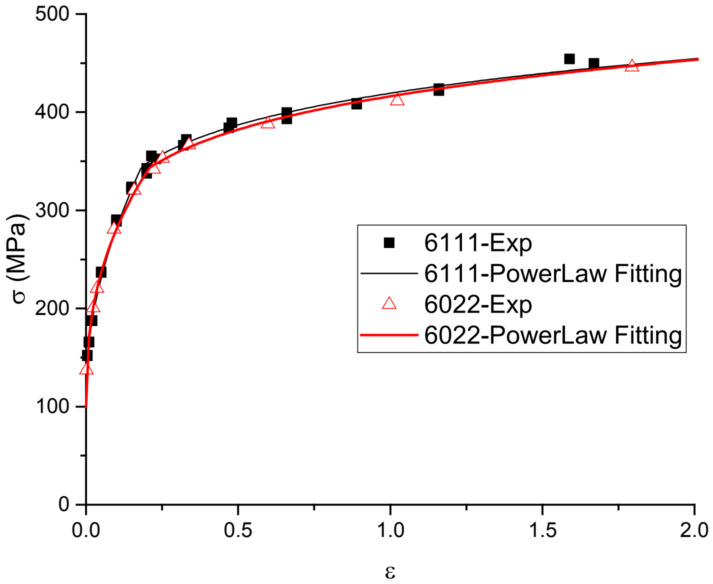
AA6111-T4: 2.26% particle



AA6022: 0.6% particle



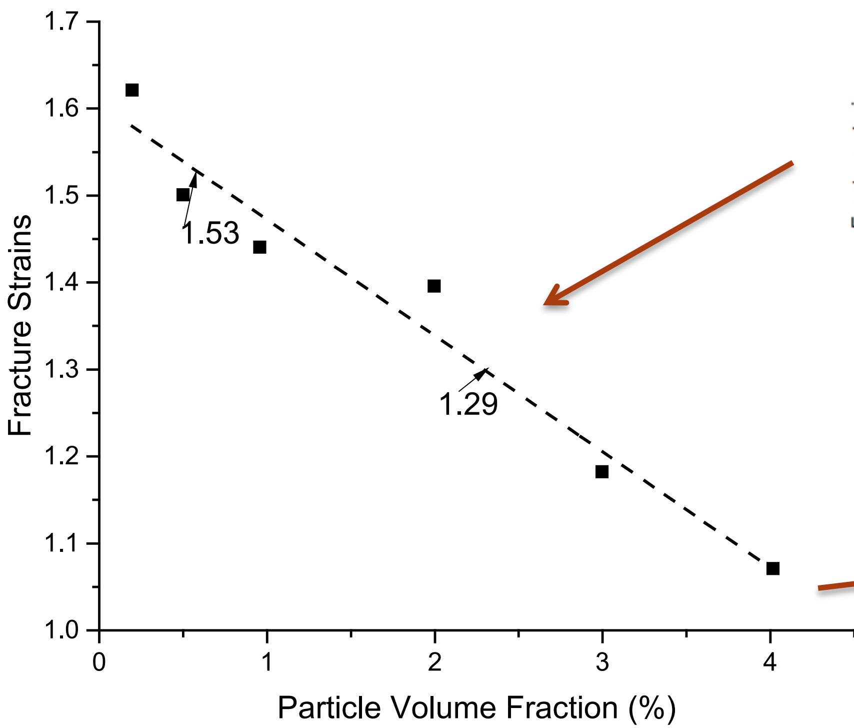


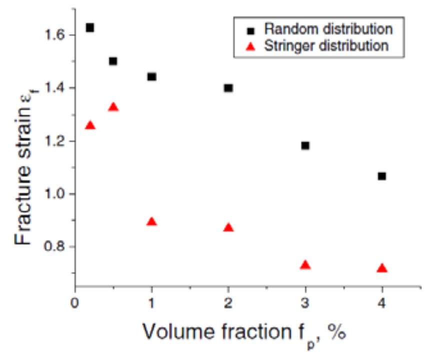
- The two alloys have very similar flow behaviors
- Both alloys have random particle distributions
  - AA6111 alloy has much higher particle volume fraction.
- The large strain flow curve is determined by accumulated rolling and tension test performed by Ford/OU at University of Windsor.

Hole Piercing to Hole Expansion:
Effects of alloys: AA6111-T4 vs AA6022

Particle volume fractions on fracture strains

Even when the flow behaviors are identical for the two Al alloys, the fracture strains of the material as a whole are considerably affected by volume fraction and distribution of hard inclusions in the alloy [1-2]. The relationship of fracture strain and particle volume fraction has been established by Hu et al. [2]





Random Particle Distribution

$$\frac{\varepsilon_f^{0.6\%}}{\varepsilon_f^{2.26\%}} \approx \frac{1.53}{1.29} \approx 1.19$$

Fracture strain vs. Particle volume fraction [2]

[1] X. H. Hu, M. Jain, P. D. Wu, D. S. Wilkinson, R. K. Mishra, *Journal of Materials Processing Technology* **2010**, *210*, 1232
[2] X. H. Hu, D. S. Wilkinson, M. Jain, R. K. Mishra, *International Journal of Fracture* **2010**, *164*, 167

Hole Piercing to Hole Expansion:
Effects of alloys: AA6111-T4 vs AA6022

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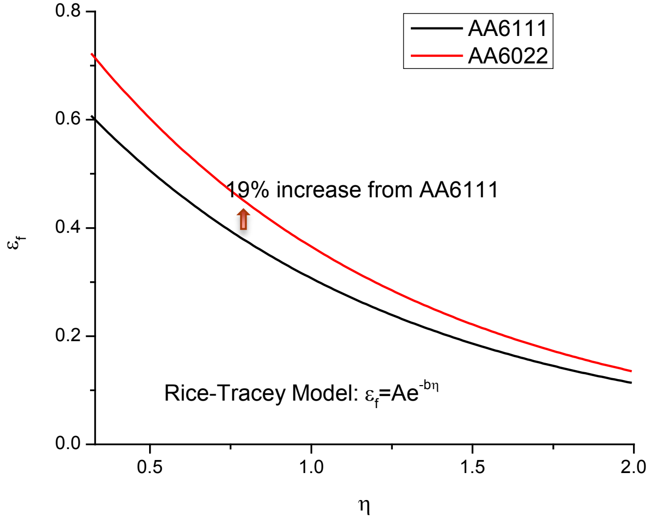
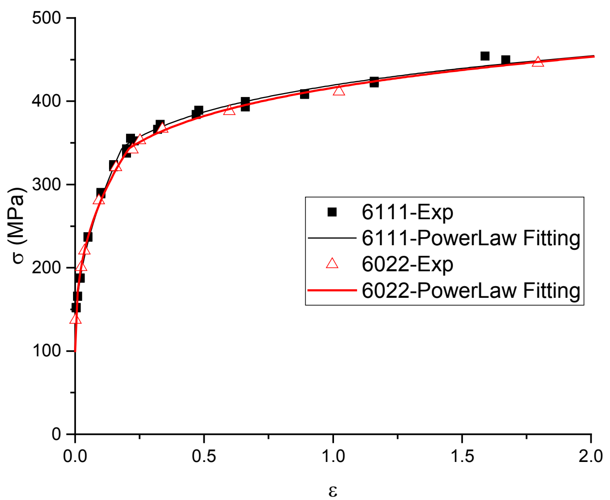
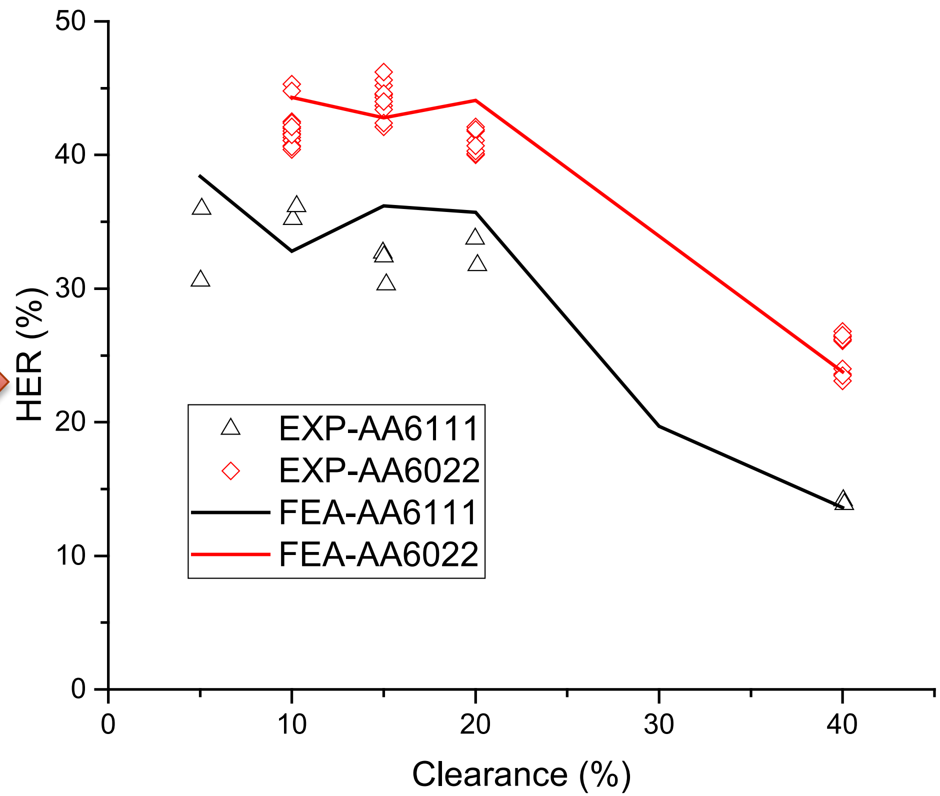
Prediction and experiments





Experimental validation



The experimental results of critical hole expansion ratios were obtained by Ford/OU.

Collaborations

- Experimentally obtain hardening parameters at large strains for different aluminum alloys (Ford+OU+UWindsor)
- Experimentally obtain quantitative relationship between edge stretchability and edge quality indicators (Ford+OU).
- Develop predictive modeling capability linking trimming conditions to edge stretchability (PNNL)
- Develop optimized process parameters based on ability of sheared surface to stretch (PNNL+Ford).
- Lab scale prototype and component scale demonstration (Ford + PNNL)

Responses to Previous Year Reviewers' Comments

Approach to performing the work:

- The reviewer inquired about how the sheet preparation process, if critical, could be implemented at a reasonable cost in factory floors. To this person, the criticality of the preparation process goes against production improvements; one part of the research is missing here.

Response: We agree the current implementation will likely increase cost. Should aluminum edge stretchability become even more important in wider applications of various aluminum alloys, the next reasonable project would be to look for cost-effective implementations to achieve the desired trimmed edge conditions.

- This reviewer stated it was difficult to assess the universality of the results and insights due to the lack of detail in the scientific process of putting the damage details into the model.

Response: The detailed processes involved in the integrated simulation and experimental process are now published in various peer-reviewed journal publications.

Proposed future research

- The reviewer indicated that future plans address work that needs to be finished to bring the project to a reasonable conclusion; however, dissemination of the information should be explicitly stated in the future plans list (even though recognition of its importance is implied).

Response: This is a good suggestion. Publication is now explicitly stated.

- The reviewer pointed out that this is the end of the project, but the reviewer hoped that it will be continued with a better integration of the process into the factory floor.

Response: We agree.

Presentation Summary

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- Relevance
  - Aluminum trimmed edge stretch formability is highly dependent on the processes that prepare the edges. This project develops innovative edge trimming methods/conditions to improve room temperature edge stretechability by 50%.
- Approach
  - An integrated experimental-modeling approach is used where validated models are used to guide and shorten process development cycle.
- Technical Accomplishments
  - Validated stretchability model is developed with trimmed/hole-pierced edge condition incorporated -PNNL
  - Different methods in improving edge stretchability by 50% identified-PNNL/Ford
  - Model prediction capability is validated by two aluminum alloys hole-piercing to hole expansion HER test.
- Collaborations
  - OEM (Ford) and academia (OU)
- Future work
  - Finish several project joint publications